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Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for biodiesel: A review

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ABSTRACT

The world today is faced with serious global warming and environmental pollution. Besides, fossil fuel will become rare and faces serious shortage in the near future. This has triggered the awareness to find alternative energy as their sustainable energy sources. Biodiesel as a cleaner renewable fuel has been considered as the best substitution for diesel fuel due to it being used in any compression ignition engine without any modification. The main advantages of using biodiesel are its renewability and better quality of exhaust gas emissions. This paper reviews the production, performance and emission of palm oil, Jatropha curcas and Calophyllum inophyllum biodiesel. Palm oil is one of the most efficient oil bearing crops in terms of oil yield, land utilization, efficiency and productivity. However, competition between edible oil sources as food with fuel makes edible oil not an ideal feedstock for biodiesel production. Therefore, attention is shifted to non-edible oil like Jatropha curcas and Calophyllum inophyllum. Calophyllum inophyllum oil can be transesterified and being considered as a potential biodiesel fuel. Compared to Palm oil and Jatropha biodiesel industry, biodiesel from Calophyllum inophyllum is still in a nascent state. Therefore, long term endurance research and tribological studies need to be carried out before Calophyllum inophyllum oil base biodiesel can become an alternative fuel in future.

Contents

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1. Introduction

The increasing industrialization, modernization and development have led to high demand of petroleum worldwide. Global energy consumption in 2008 was growing from 6630 million tonnes of oil equivalent (Mtoe) in 1980 to almost double of the energy consumption which had reached 11,295 Mtoe in 2008 [1]. However, the world reserve for fossil fuel such as petroleum has been depleting and causing the price to hit new highest record of US$ 136 per barrel in July 2008 [2]. In Malaysia, the final energy consumption has risen at an annual growth rate of 7.2% from 1990 to 2008 and reached 44.9 Mtoe in 2008 [3]. The crucial challenge faced by power sector in Malaysia currently is the issue of sustainability. Besides, the world today is faced with a serious global warming and environmental pollution. The major sources of greenhouse gas (GHG) emissions are gasoline and diesel fuel from transportation sector. The world is confronted with the twin crises of fossil fuel depletion and environmental degradation [4]. Thus, there is an urgent need to find an alternative renewable energy resource that is renewable, clean, reliable and yet economically feasible. Biodiesel, a cleaner renewable fuel has been considered as the best candidate for diesel fuel substitution due to it can be used in any compression ignition engine without any modification on the engine.

Biodiesel is gradually gaining acceptance in the market as an environmentally friendly fuel and the demand is expected to increase sharply as an alternative renewable energy source in the near future. Biodiesel fuel is mono alkyl ester derived from vegetable or animal and it can be blended with diesel fuel which has characteristics similar to diesel fuel and has lower exhaust emissions [5–7]. On the other hand, the main drawbacks of vegetable oil have to overcome due to the high viscosity and low volatility which will cause a poor combustion in diesel engines. Transesterification is the process successfully employed to reduce the viscosity of biodiesel and improve the other characteristics [8]. Currently, more than 95% of the world biodiesel is produced from edible oil which is easily available on a large scale from the agricultural industry. However, competition of edible oil sources as food with fuel makes edible oil not an ideal feedstock for biodiesel production [9–10]. Therefore, much effort is required to focus in this area to produce biodiesel from non-edible seeds like Jatropha curcas, Pongamia pinnata, Calophyllum inophyllum, etc. to become feasible feedstock for biodiesel.

Biodiesel seems to be a realistic alternative renewable fuel in the near future and this review is focus on the possibilities of using palm oil, Jatropha curcas, Calophyllum inophyllum and biodiesel in diesel engine. Besides, the fuel characteristics, processes available, production, performance and emission analysis of biodiesel are discussed by making a comparison on these three different types of biodiesel fuel.

2. Biodiesel

The concept of using biofuel in diesel engines is not a radically new idea, an inventor named Rudolph Diesel demonstrated his first developed compression ignition (CI) diesel engine using peanut oil as a fuel at the World Exhibition at Paris in 1900 [11–12]. However due to abundant supply of diesel and vegetable oil fuel were more expensive than diesel, research and development activities on vegetable oil were not seriously pursued [13]. There is a renewed interest in vegetable oil in this decade when it was conclusively realized that petroleum fuel are dwindling fast and environmental friendly renewable substitutes must be identified [14]. Biodiesel is gaining more and more interest as an attractive fuel due to the depleting nature of fossil fuel resources and environmental protection reason.

Vegetable oil which also known as triglycerides have the chemical structure as shown in Fig. 1 comprise of 98% triglycerides and small amounts of mono and diglycerides [15]. Biodiesel is defined as the mono alkyl esters of vegetable oil or animal fats. It is the process of reacting triglyceride with an alcohol in the presence of a catalyst to produce glycerol and fatty acid esters [14]. Vegetable oil contains fatty acid, free fatty acids, phospholipids, phosphatides, carotenes, tocopherols, sulphur compound and traces of water [16]. The fatty acids commonly found in vegetable oil are stearic, palmitic, oleic, linoleic and linolenic and the summary of the fatty acid composition of some the common vegetable oil is shown in Table 1 [9,12,16–17]. Vegetable oil can be used as liquid engine fuel in various ways such as straight vegetable oil, oil blends, pyrolysis, micro-emulsification and transesterification in diesel engine [18].

Biodiesel which has combustion characteristics similar to diesel and biodiesel blends has shorter ignition delay, higher ignition temperature and pressure as well as peak heat release compare to diesel fuel [5]. Moreover, the engine power output and brake power efficiency was found to be equivalent to diesel fuel. Biodiesel and diesel blends can reduce smoke opacity, particulate matters, un-burnt hydrocarbons, carbon dioxide and carbon monoxide emissions but nitrous monoxide emissions have slightly increased [19]. However, the main drawback of biodiesel fuel is their high viscosity and low volatility, which causes poor combustion in diesel engines including formation of deposits and injector cocking due to poorer atomization upon injection into the combustion chamber. Transesterification of the oil reduces the viscosity of the oil to a range of 4–5 mm^2/s closer to that of diesel and hence improves combustion [20–21]. Biodiesels or fatty acid esters are efficient, clean and natural energy alternative to petroleum fuel. The use of biodiesel has grown dramatically during the last few years. Feedstock costs account for a large portion of the direct biodiesel production costs, including capital cost and return [22].

2.1. Standard of biodiesel

In general terms, biodiesel may be defined as a domestic renewable fuel for diesel engines derived from natural oil like palm, soybean and rapeseed oil that meet the specifications of ASTM D

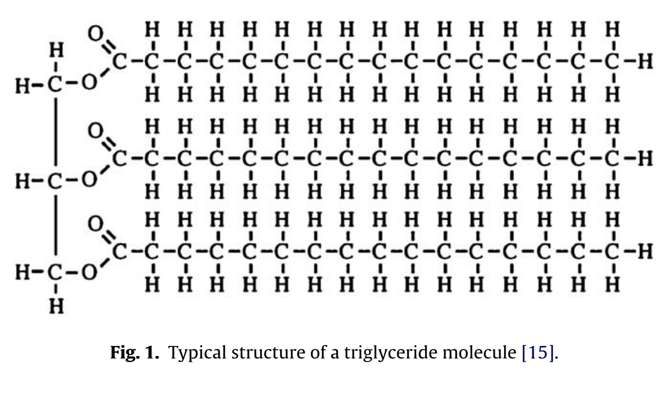

Fig. 1. Typical structure of a triglyceride molecule [15].

Table 1
Chemical structure for common vegetable oil of fatty acids.

Name	Chemical name	Structure (*xx*:*y*)[a]	Formula
Lauric	Dodecanoic	12:0	$C_{12}H_{24}O_2$
Myristic	Tetradecanoic	14:0	$C_{14}H_{28}O_2$
Palmitic	Hexadecanoic	16:0	$C_{16}H_{32}O_2$
Stearic	Octadecanoic	18:0	$C_{18}H_{36}O_2$
Oleic	cis-9-Octadecenoic	18:1	$C_{18}H_{34}O_2$
Linoleic	cis-9,cis-12-Octadecadienoic	18:2	$C_{18}H_{32}O_2$
Linolenic	cis-9,cis-l2,cis-15-Octadecatrienoic	18:3	$C_{18}H_{30}O_2$
Arachidic	Eicosanoic	20:0	$C_{20}H_{40}O_2$
Gadoleic	11-eicosenoic	20:1	$C_{20}H_{38}O_2$
Behenic	Docosanoic	22:0	$C_{22}H_{44}O_2$
Erucle	cis-13-Docosenoic	22:1	$C_{22}H_{42}O_2$
Lignoceric	Tetracosanoic	24:0	$C_{24}H_{48}O_2$

[a] *xx* = total number of carbon atoms and *y* = number of double bonds.

Table 2
Technical properties of biodiesel [23].

Common name	Biodiesel
Common chemical name	Fatty acid (m)ethyl ester
Chemical formula range	C_{14}–C_{24} methyl esters or $C_{15-25}H_{28-48}O_2$
Kinematic viscosity range (mm^2/s, at 313 K)	3.3–5.2
Density range (kg/m^3, at 288 K)	860–894
Boiling point range (K)	>475
Flash point range (K)	420–450
Distillation range (K)	470–600
Vapour pressure (mm Hg, at 295 K)	<5
Solubility in water	Insoluble in water
Physical appearance	Light to dark yellow, clear liquid
Odour	Light musty/soapy odour
Biodegradability	More biodegradable than petroleum diesel
Reactivity	Stable but avoid strong oxidizing agents

6751 or EN 14214. Technical properties of biodiesel are given in Table 2 [23]. Biodiesel is a clear amber-yellow liquid with a viscosity similar to diesel fuel. Biodiesel is non-flammable with a flash point of 423 K for biodiesel as compared to 337 K for diesel.

The biodiesel standard testing materials are American standards ASTM D6751 and European Union standard EN 14214 for biodiesel fuel [24]. American standard ASTM D6751 identifies the parameters the pure biodiesel (B100) must meet before being used as a pure fuel or being blended with petroleum-based diesel fuel. Biodiesel (B100) specifications ASTM D6751-06 standard is shown in Table 3 [25]. However, European Union standard EN 14214 describes the minimum requirements for FAME (fatty acid methyl ester) as summarized Table 4 [23]. The quality of biodiesel fuel can be significantly influenced by numerous factors among others include: the quality of feedstock, fatty acid composition of the vegetable oil, animal fats and waste oil, type of production and refining process employed and post-production parameters.

2.2. Sources (feedstock) of biodiesel

There are more than 350 oil-bearing crops identified, among typically only soybean, palm, sunflower, rapeseed and peanut oil are considered as potential alternative fuel for diesel engines [26–27]. New plant oil that is under consideration includes mustard seed, Jatropha curcas, cotton seed and Calophyllum inophyllum oil. Vegetable oil is renewable fuel and become more attractive recently due to their environmental benefits as well as it's from renewable resources. Driven by increasing population, rising standards of living and disposable incomes in developing countries, the world vegetable oil market is projected to reach 138 million metric tonnes by the year 2010 [28]. World vegetable oil consumption is shown in Table 5 [29]. Worldwide consumption of palm oil is the highest in 2009 which is 41.7 million metric tonnes.

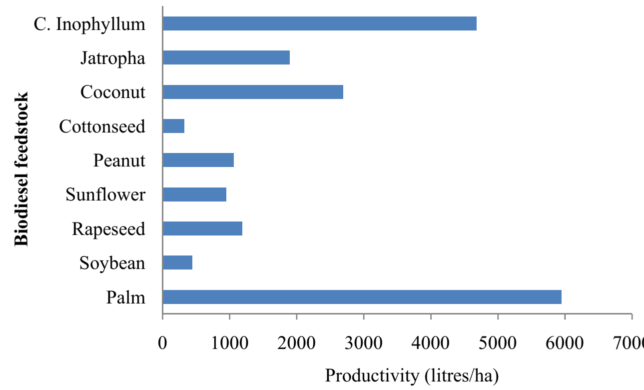

Fig. 2. Production oil yield for various source of biodiesel feedstock [50].

The source for biodiesel production is usually chosen according to the availability in each region or country. European community are self-dependent in production of edible oil and even have surplus amount to export. Hence, edible oil such as rapeseed is used in European Nations [30–31]. Besides, soybeans [32–33] are commonly used in the United States for food products which has led to soybean biodiesel becoming the primary source for biodiesel in this country [34]. Similarly countries with coastal area such as Malaysia, Indonesia and Thailand have surplus palm oil [35] and coconut oil [36], therefore which is utilized for the synthesis of biodiesel [37]. However, some Asian countries are not self sufficient in edible oil and exploring non-edible seed oil, like Jatropha [38–39] and Karanja (Pongamia pinnata) [40] as biodiesel raw materials. Jatropha and Karanja oil is used as a significant fuel source for biodiesel in India and Southeast Asia [41]. In Brazil, the most used oil source for the biodiesel productions are soybean, castor bean and palm kernel [42–43]. There are other different oil sources reported in scientific articles such as sunflower oil [44], cotton seed oil [45], pomace oil [46], canola oil [47], peanut oil [48] and Calophyllum inophyllum oil [49] are potential sustainable oil sources for biodiesel production.

Fig. 2 shows the oil yield of various oil sources for biodiesel feedstock [50]. Palm oil possesses potential due to high production rate to meet the future demand and it has high oil content. As noted in the figure, the highest oil productivity is oil palm (5950 litres per hectare) which is about 13 times better than soybean oil and follows by Calophyllum inophyllum oil. Life cycle analysis (LCA) conducted on various biodiesels revealed that palm oil-based biodiesel can reduce greenhouse gases (GHG) emission by 62% as compared to soybean oil (40%), rapeseed oil (45%) and sunflower oil (58%) [51].

3. Palm oil

Oil palm is botanical classification as *Elaeis guineensis* and native to the West Africa where it was growing wild and later developed into an agricultural crop [52]. *Elaeis guineensis* Jacq is the most productive oil palm variety which can produce 10–35 tonnes/ha of fresh fruit bunch (FFB) oil palm annually [53]. The oil palm is a tropical perennial plant and grows well in lowland with humid places and therefore it can be cultivated easily in Malaysia [54]. The tree which is unbranched and single-stemmed can grow up to 20–30 m height [55]. The flowers are produced in dense clusters which each individual flower is small with three sepals and three petals. The leaves are pinnate and can reach between 3 and 5 m long. The fleshy orange reddish coloured fruits grow in large and tight female bunches each fruit weigh as much as 10–40 kg and

Table 3
ASTM D6751-06 standard properties for biodiesel (B100) [23,24].

Property	ASTM method	Limits	Units
Flash point	D93	130 min	°C
Water and sediment	D2709	0.050 max	vol.%
Kinematic viscosity, 40 °C	D445	1.9–6.0	mm^2/s
Sulphated ash	D874	0.020 max	mass%
Sulphur	D5453	–	–
S15 grade	–	15 max	ppm
S500 grade	–	500 max	ppm
Copper strip corrosion	D130	No. 3 max	–
Cetane Number	D613	47 min	–
Cloud point	D2500	Report	°C
Carbon residue 100% sample	D4530	0.050 max	mass%
Acid number	D664	0.80 max	mg KOH/g
Free glycerine	D6584	0.020 max	mass%
Total glycerine	D6584	0.240 max	mass%
Phosphorus content	D4951	0.001 max	mass%
Distillation temperature, 90% recovered	D1160	360 max	°C
Sodium/potassium	UOP391	5 max combined	ppm

Table 4
European Union standard (EN 14214) properties for biodiesel [23,24].

Property	Test-method	Lower limit	Upper limit	Units
FAME content	pr EN 14103	96.5	–	% (m/m)
Density at 15 °C	EN ISO 3675/EN ISO 12185	860	900	kg/m^3
Viscosity at 40 °C	EN ISO 3104	3.5	5.0	mm^2/s
Flash point	EN CD 3679e	>101	–	°C
Sulphur content	–	–	10	mg/kg
Tar remnant (at 10% distillation remnant)	EN ISO 10370	–	0.3	% (m/m)
Cetane number	EN ISO 5165	51.0	–	–
Sulphated ash content	ISO 3987	–	0.02	% (m/m)
Water content	EN ISO 12937	–	500	mg/kg
Total contamination	pr EN 12662	–	24	mg/kg
Copper band corrosion (3 h at 50 °C)	EN ISO 2160	Class 1	Class 1	rating
Oxidation stability, 110 °C	pr EN 14112k	6	–	h
Acid value	pr EN 14104	–	0.5	mg KOH/g
Iodine value	pr EN 14111	–	120	–
Linoleic acid methyl ester	pr EN 14103d	–	12	% (m/m)
Polyunsaturated (≥4 double bonds) methyl ester	–	–	1	% (m/m)
Methanol content	pr EN 14110l	–	0.2	% (m/m)
Monoglyceride content	pr EN 14105m	–	0.8	% (m/m)
Diglyceride content	pr EN 14105m	–	0.2	% (m/m)
Triglyceride content	pr EN 14105m	–	0.2	% (m/m)
Free glycerine	pr EN 14105m/pr EN 14106	–	0.02	% (m/m)
Total glycerine	pr EN 14105m	–	0.25	% (m/m)
Group I metals (Na + K)	pr EN 14108/pr EN 14109	–	5	mg/kg
Group II metals (Ca + Mg)	pr EN 14538	–	5	mg/kg
Phosphorus content	pr EN14107p	–	4	mg/kg

contain up to 2000 fruitlets as shown in Fig. 3 [56]. The oil palm plantations in Malaysia are planted with a density of 148 palms per hectare. The fruitlet consists of a fibrous mesoscarp layer and the endocarp (shell) containing the kernel which contains oil and carbohydrate reserves for the embryo as shown in Fig. 4 [6,57]. The economic life of oil palm tree is 20–25 years of its lifespan of 200 years [53].

Oil palm is the highest oil yield crop producing on average about 4–5 tonnes of oil/ha annually which is about 10 times the yield of soybean oil [58]. There are two main products produced by the oil palm fruit they are crude palm oil and crude palm kernel oil. Crude palm oil is obtained from the mesocarp and kernel oil is obtained from the endosperm (kernel). However, the main wastes and by-product from oil palm oil are the empty fruit bunches, palm oil mill

Table 5
World vegetable oil consumption (million metric ton) [29].

Vegetable oil	1999	2000	2001	2002	2003	2004	2006	2007	2008	2009
Palm	21.2	23.3	25.2	25.8	28.4	30.5	38.1	40.8	40.2	41.7
Soybean	24.5	26	28.9	30.5	31.6	31.6	35.7	38.4	37.5	35.7
Rapeseed	13.3	13.1	12.4	11.6	14.0	15.5	17.8	18.0	18.4	19.9
Sunflower seed	9.5	8.6	7.7	8.3	9.0	8.6	10.2	10.1	9.0	10.8
Palm kernel	2.6	2.7	3.2	3.2	3.5	3.6	4.3	4.8	4.8	5.3
Peanut	4.3	4.2	4.8	4.4	4.9	5.0	4.9	5.0	4.8	4.9
Cottonseed	3.7	3.6	3.8	3.5	3.7	4.6	4.8	4.9	5.0	4.8
Coconut	3.2	3.3	3.4	3.4	3.4	3.4	3.3	3.3	3.4	3.5
Olive	2.4	2.5	2.5	2.5	2.6	2.7	2.9	3.0	2.9	3.0
Total	84.7	87.3	91.9	93.2	101.1	105.5	122.0	128.3	126.0	129.6

Fig. 3. Oil palm tree and fruits.

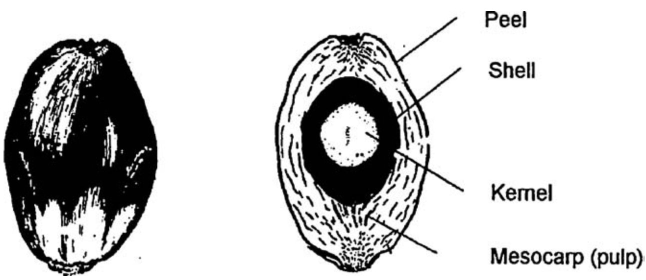

Fig. 4. Fresh oil palm fruit and its longitudinal section [57].

Table 6
The dry weight composition of fresh ripe fruit and mesocarp for oil palm [59].

Fruit	Dry weight (%)	Mesocarp	Dry weight (%)
Palm oil	29	Palm oil	46–50
Water	27	Palm oil (dry basis)	77–81
Residue	8	Moisture	36–40
Shell	30	Non-fatty solids	13–15
Kernel	6		

effluent, sterilizer condensate, palm fibre and palm kernel shell. The mesocarp contains about 49% of palm oil and the kernel about 50% of palm kernel oil. Table 6 shows the dry weight composition fresh ripe fruit and mesocarp for oil palm [59].

Global demand for edible oil is increasing in this few decades which cause a tremendous increase in the area of oil crop cultivation especially soybean and oil palm. The world production of palm oil is 45 million tonnes and highest production is in South East Asia with a total 89% of total palm oil production (40% in Malaysia, 46% in Indonesia, 3% in Thailand) as shown in Fig. 5 [60–61]. In Malaysia a total 4.5 million hectares of land is occupied under oil palm cultivation. It produced 17.73 million tonnes of palm oil and contributed

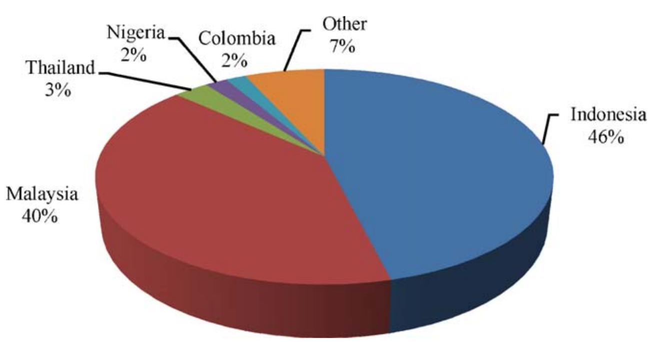

Fig. 5. World palm oil production 2009 [60].

Table 7
Oil palm biomass components and potential energy generated [62].

Oil palm component	Quantity (million tonnes)	Calorific value (kJ/kg)	Potential energy generated (Mtoe)
Empty fruit bunch	17.00	18,838	7.65
Mesocarp Fibre	9.6	19,096	4.37
Shell	5.92	20,108	2.84
Palm kernel	2.11	18,900	0.95
Total	34.63		15.81

about RM 65.19 billion to the Malaysia export in 2008. Malaysia has approximately 362 palm oil mills, processing 71.3 million tonnes of fresh fruit bunch and producing an estimated 19 million tonnes of crop residue annually in the form of empty fruit bunch, fibre and shell. Table 7 shows the calorific values and moisture content of these residues which can be used for electricity generation [62]. Palm oil is one of the most efficient oil bearing crops in terms of land utilization, efficiency and productivity.

4. Jatropha curcas

Jatropha curcas is a large shrub that belongs to the genus *Euphorbiaceae* native in tropical American but widely distributed in tropical and subtropical regions throughout Africa, India and South East Asia [63]. It is a tropical plant that can be grown in low to high rainfall areas either in the farms as a commercial crop or on the boundaries of fields as a hedge [64]. It requires very little irrigation and grows in all types of soils. Jatropha is well adapted to semi-arid conditions, although more humid environmental conditions result better crop performance. The Jatropha plant is a drought-resistant and has the capability to grow on marginal soils. It is a hardy and highly adaptable crop that can grow in marginal soils and capable to reclaim wasteland. The plant spread far beyond its original distribution due to the properties of the plant easy to establish, hardness, rapid growth, easy propagation and wide range of useful [65].

In some countries like India which faces a deficient of edible oil, Jatropha oil becomes the choice for biodiesel. The Jatropha plant has a long productive period with effective yield up to 50 years and yielding large returns annually. The production of the seeds is about 0.8 kg/m^2 per year [66]. The oil content of seed ranges from 30% to 50% by weight and the kernel ranges from 45% to 60% [67]. The fatty acid composition of Jatropha classifies it as a linoleic or oleic acid type, which are unsaturated fatty acids. Fresh Jatropha is a slow drying, odourless and colourless oil and become yellow after aging as shown in Fig. 6. The average production of Jatropha oil on average soil will give 1.6 Million tonnes/ha oil [38].

Jatropha oil which is a branched triglycerides type of non-edible vegetable oil is a potential alternative diesel fuel. Its methyl ester properties are close to diesel fuel and able to reduce CO_2 to the

Fig. 6. Jatropha plant and seed.

atmosphere when it is utilized in diesel engine. However, direct burning of Jatropha oil in diesel engine faces many problems related to viscosity which is around ten times higher than diesel. The high viscosity of the oil is due to their large molecular weight and chemical structure [68]. Therefore, a reduction in viscosity is of prime importance to make Jatropha oil a suitable alternative fuel for diesel engines. Several approaches to reduce the problem of high viscosity are preheating the oil, microemulsion with solvents, dilution with diesel fuel, thermal cracking or pyrolysis and transesterification [67,69]. Jatropha in particular has an extra advantage over other non-edible oil sources due to its drought-resistant plant capable of surviving in abandoned and fallowed agricultural land [18]. Therefore, the potential of using Jatropha as a feedstock for biodiesel production has attracted much attention. Compared to palm oil biodiesel industry, biodiesel produced from Jatropha is still in its nascent state in Malaysia [35].

5. Calophyllum inophyllum

Calophyllum inophyllum, commonly known as Penaga Laut in Malaysia, is an non-edible oilseed ornamental evergreen tree belonging to the *Clusiaceae* family as shown in Fig. 7 [70–71]. The scientific name of "*Calophyllum*" comes from the Greek word for "*beautiful leaf*". It grows along coastal areas and adjacent lowland forests, although it occasionally occurs inland at higher elevations. It is native of eastern Africa, southern coastal India, Southeast Asia, Australia and the South Pacific. Calophyllum inophyllum is also often called as 'Alexandrian Laurel' in English and other vernacular names in various countries as shown in Table 8 [72].

Table 8
Vernacular names for Calophyllum inophyllum [72,74,131].

Country	Vernacular names
Bangladesh	Punnang
Cambodia	Khtung, Kchyong
English	Alexandrian laurel, Borneo mahogany, Tamanu
Hawaii	Kamani
India	Polanga, Sultan Champa
Indonesia	Nyamplung, Bintangur
Malaysia	Penaga Laut, Bintangor
Myanmar	Ponnyet
Palau	Btaches
Papua New Guinea	Beach calophyllum
Philippines	Butalau, palo maria, bitaog
Thailand	Krathing, saraphee (northern), naowakan (Nan)

Fig. 7. Calophyllum inophyllum plant and seed [71].

Fig. 8. Ripe fruit (left), cracked shell showing seed kernel inside (middle), and dry seed (right) [71].

Calophyllum inophyllum is a medium and large-sized evergreen sub-maritime tree that averages 8–20 m (25–65 ft) in height with a broad spreading crown of irregular branches. It has elliptical, shiny and tough leaves. The flower is around 25 mm wide and occurs in racemose or paniculate inflorescences consisting of 4–15 flowers. The fruit (ballnut) is a round, green drupe reaching 2–4 cm (0.8–1.6 in.) in diameter and having a single large seed as shown in Fig. 8 [71]. When it is ripe, the fruit is wrinkled and its colour varies from yellow to brownish-red. The grey, ligneous and rather soft nut contains a pale yellow kernel, which is odourless when fresh. Calophyllum inophyllum kernels have very high oil content (75%) and the oil contains approximately 71% of unsaturated fatty acids (essentially oleic and linoloeic acids) [73]. It is obtained by cold expression and yields refined, greenish yellow oil, similar to olive oil, with an aromatic odour and an insipid taste. Fruits are usually borne twice a year and it produces up to 100 kg of fruits and about 18 kg of oil [74]. Calophyllum inophyllum is grown in warm temperatures in wet or moderate conditions and requires mean annual rainfall around 1000–5000 mm [71]. It is highly tolerant to strong winds, salt spray and brackish water tables. The trees are sensitive to frost and fire. The wind and salt tolerance makes it suitable for sand dune stabilization [75]. Plantation can be done at a density of 400 tree/ha [76]. The average oil yield is 11.7 kg-oil/tree or 4680 kg-oil/ha.

5.1. Usage of Calophyllum inophyllum

Traditional Pacific Islanders used Calophyllum wood to construct the keel of their canoes while the boat sides were made from breadfruit wood. In Java, the tree is believed to have diuretic properties. The emetic and purgative gum extracted from the plant is used for the treatment of wounds and ulcers. An infusion of gum, bark and leaves is used for sore eyes [74]. Calophyllum inophyllum oil from the fruit traditionally has been used for medicine and cosmetics. It has been used empirically for centuries in Madagascar to treat wound, facial neuralgia, skin ailment and hair loss. Moreover, it is used in acute skin irritation including burns, rashes, impetigo, insect bites and abrasions [77]. It is also applied topically in cases of rheumatism. Besides, the oil is used in varnishes and as lamp oil. In Southern India, the oil of the seeds is used specifically for treating skin diseases [78]. The fruits are used for human consumption although they are reported to be slightly toxic. Crude Calophyllum inophyllum oil generally has high acid value 44 mg KOH/g (22% FFAs) and thus a dependable technique for converting this Calophyllum inophyllum oil to biodiesel is very much required. The fatty acid methyl ester of Calophyllum inophyllum seed oil meets all of the major biodiesel requirements in the United States standard (ASTM D 6751-06) and European Union standard (EN 14214) [76]. According to Sahoo et al. [20], it is shown that the chemical characteristics of the Calophyllum inophyllum oil methyl ester were found to be in the close range of diesel engine requirement. However, further research and study need to be carried out before suggesting long term application of Calophyllum inophyllum oil based biodiesel.

5.2. Current development on Calophyllum inophyllum oil

Forest Research Institute Malaysia (FRIM) and Forestry Research and Development Agency, Indonesia (FORDA) had joint forestry research and development together especially in biofuel area from year 2007 to 2010 for 5 years [79]. In 2009, a group of researchers from FRIM had joined training on Calophyllum inophyllum as biofuel to research and exchange information about Calophyllum inophyllum as an alternative biodiesel fuel conducted by FORDA in Indonesia [80]. This is the very first step Malaysia involved in Calophyllum inophyllum research as a biodiesel fuel.

The cultivation of Calophyllum inophyllum oil can be considered as a potential alternative for renewable energy sources and the oil could be transesterified. However, there are very limited information is available about the research and production of biodiesel from Calophyllum inophyllum oil. Therefore, further study and research Calophyllum inophyllum fuel property measurement, long-term wear and tribological analysis of biodiesel, injection timing and duration for better combustion of biodiesel in diesel engines need to be carried out.

6. Production of biodiesel

Researchers have developed many different methods for biodiesel production from different feedstocks. A review of these methods from palm oil, Jatropha curcas and Calophyllum inophyllum have discussed here.

6.1. Palm biodiesel

The production of fatty acid methyl ester (FAME) from palm fatty acid distillate (PFAD) having high free fatty acids (FFA) was presented by Chongkhong et al. [43]. The optimum condition for the continuous esterification process is molar ratio of methanol to PFAD at 8:1 with 1.834 wt% of H_2SO_4 at 70 °C. The amount of FFA was reduced from 93 wt% to less than 2 wt%. The FAME was purified by neutralization with 3 M sodium hydroxide in water solution at a reaction temperature of 80 °C for 15 min followed by transesterification process with 0.396 M sodium hydroxide in methanol solution at a reaction temperature of 65 °C for 15 min [43]. In the other hand, the transesterification of palm oil to methyl esters using KOH loaded on Al_2O_3 and NaY zeolite as heterogeneous catalysts was studied by Noiroj et al. [81]. The 25 wt% KOH/Al_2O_3 and 10 wt% KOH/NaY catalysts are suggested to be the best formula due to catalyst amount of 3–6 wt% and the biodiesel yield of 91.07% at temperatures below 70 °C with molar ratio of palm oil to methanol at 1:15. The authors concluded that the type of support strongly affects the activity and leaching of the active species of the catalyst [81]. Besides, Crabbe et al. [82] analyzed biodiesel production from crude palm oil and evaluation of butanol extraction. The palm oil methyl ester was used as an extracting in batch and continuous acetone–butanol–ethanol (ABE) fermentation. The optimized variables molar ratio at 40:1 methanol to palm oil with 5% H_2SO_4 (vol/wt) reacted at 95 °C gave a maximum

ester yield of 97%. Biodiesel preferentially extracted butanol and enhanced its production in the batch culture from 10 to 12 $g\,l^{-1}$. The biodiesel–ABE mixture had the higher cetane number.

The study of transesterification for palm oil via heterogeneous process using montmorillonite KSF as heterogeneous catalyst was presented by Kansedo et al. [83]. It was shown that the palm oil fatty acid methyl esters (FAME) yield could reach up to 79.6% at temperature 190 °C with molar ratio of methanol to oil 8:1, 3% of catalyst and reaction period at 180 min. Apart from that, Gao et al. [84] concluded that with 5% KF/Ca–Al (80 wt% $KF\cdot 6H_2O$) catalyst under temperature 338 K and methanol to oil molar ratio 12:1, after 5 h reaction, the FAME yield could reach 97.98%. However, with the mass ratio100 wt% of $KF\cdot 6H_2O$ of catalyst under the same reaction condition only need 3 h to get the FAME yield of 99.74%. A Study revealed that employing non-catalytic supercritical methanol technology to produce biodiesel from palm oil [85]. The research was carried out in a batch-type tube reactor and heated beyond supercritical temperature and pressure of methanol, which are at 239 °C and 8.1 MPa respectively. The results showed that non-catalytic supercritical methanol technology required a mere 20 min reaction time to produce 72% yield of FAME with a temperature 360 °C and molar ratio of palm oil to methanol at 1:30 [85].

The production of biodiesel from crude palm oil via C. rugosa lipase-catalyzed hydrolysis followed by Novozym 435-catalyzed esterification was investigated by Talukder et al. [86–88]. Novozym 435 catalyzed methyl esterification of fatty acids progressed much faster than methanolysis of crude palm oil. The two-step process gave higher biodiesel yield (98%) than the single-step Novozym 435-catalyzed methanolysis in t-butanol mediated system (92%) and the solvent free system with three successive additions of methanol (92%) [86]. The study of acid catalyzed homogeneous esterification reaction for biodiesel production from palm fatty acids was presented by Aranda et al. [89]. The study shows that methanesulphonic and sulphuric acid were the best catalysts and reaction with methanol obtained greater yields. At optimized reaction conditions a palm oil methyl ester conversion up to 100% could be achieved in transesterification using the liquid core encapsulated lipase [90]. Melero et al. [91] produced a FAME yield of 95% in 4 h of reaction with a moderate methanol to oil molar ratio 20:1, at temperature 140 °C using sulphonic acid-modified mesostructured catalysts. Hameed et al. [92] obtained the optimum biodiesel yield 89.23% using KF/ZnO catalyst with molar ratio methanol to oil 11.43:1 and reaction time 9.72 h. The yield of FAME obtained was 92.5 wt% by using alum as a heterogeneous catalyst under the conditions of methanol to oil molar ratio is 18:1, reaction time 12 h and at temperature 170 °C [93]. Ooi et al. [94] evaluated the catalytic conversion of palm oil based fatty acid mixture to liquid fuel. Tamunaidu and Bhatia [95] studied the optimum catalytic cracking of palm oil for the production using response surface methodology. Chotwichien et al. [96] conducted the utilization of palm oil alkyl esters as an additive in ethanol and butanol blends. The fuel properties results indicated that blends containing butanol have properties closer to diesel than ethanol blends. Table 9 shows the transesterification reaction using various types of catalyst for palm biodiesel.

6.2. Jatropha biodiesel

The technique of biodiesel production from crude Jatropha curcas seed oil with high free fatty acids (15% FFA) was performed by Berchmans and Hirata [97]. The high FFA level of Jatropha oil was reduced to less than 1% by a two-step pretreatment process. The first stage was acid pretreatment process, which could reduce the FFA level of Jatropha oil to less than 1% with acid value of 2 mg KOH/g-oil. The second stage is alkali base catalyzed transesterification process and final Jatropha methyl esters yield is 90%. Besides, production of biodiesel through transesterification of Jatropha oil in a heterogeneous system using KNO_3/Al_2O_3 solid catalyst was discussed by Vyas et al. [98]. The optimum conversion of 84% was achieved at 70 °C with a molar ratio of methanol to Jatropha oil 12:1 under reaction time 6 h and 6% of catalyst. KNO_3/Al_2O_3 solid catalyst was strong solid base catalyst for the transesterification of Jatropha oil with methanol and the catalyst was recyclable at least for three times [98]. Patil and Deng [99] investigated biodiesel from low-cost high FFA Jatropha oil with two transesterification processes. The two transesterification processes are 0.5% H_2SO_4 acid catalyzed esterification process at 40 °C with methanol to oil molar ratio of 6:1, and follow by oil molar ratio of 9:1 with 2% KOH alkali catalyzed transesterification reaction at 60 °C. This two-step esterification process gives yield of 90–95% for Jatropha biodiesel.

A study conducted on the preparation of biodiesel from Jatropha oil by lipase catalyst in a solvent free system [100]. The results showed that the best yield 98% was obtained using Pseudomonas cepacia lipase immobilized on celite at 50 °C in the presence of 4–5% water for 8 h. The yields were not affected, if analytical grade alcohol was replaced by commercial grade alcohol. Tiwari et al. [101] performed the optimum combination for reducing the FFA of Jatropha curcas oil from 14% to less than 1% was found to be 1.43% H_2SO_4 acid catalyst, 0.28 (v/v) methanol to oil ratio and 88 min reaction time at a reaction temperature 60 °C. After pretreatment, the product was used for the final alkali-catalyzed transesterification reaction with methanol (0.16, v/v) to produce biodiesel in 24 min. This process gave an average yield of biodiesel above 99% and having properties satisfying the standards for biodiesel. The ultrasonic transesterification study of Jatropha curcas oil to biodiesel by a two-step process was carried out by Deng et al. [102]. The two-step processes are acid esterification and base transesterification process. The authors were observed that after the first-step pretreatment with H_2SO_4 for 1 h, the acid value of Jatropha oil was reduced from 10.45 to 1.2 mg KOH/g and subsequently, NaOH was used for the second-step transesterification. The clear yellowish Jatropha biodiesel with 96.4% yield and 0.32 mg KOH/g acid value was obtained after reaction for 0.5 h [102]. The two-step process with ultrasonic radiation is effective and time saving for biodiesel production from Jatropha oil.

Biodiesel production from Jatropha curcas crude oil (JCCO) by a two step catalyzed process using $SiO_2\cdot HF$ solid catalyst for FFA esterification step was presented by Corro et al. [103]. After that, the triglycerides present in the Jatropha oil were transesterified with methanol catalyzed by NaOH. The chromatographic analysis of the biodiesel revealed that the process proposed led to a very high quality biodiesel and meeting the international requirements for its utilization as a fuel. Besides, Lu et al. [104] obtained the Jatropha biodiesel yield by transesterification was higher than 98% in 20 min using 1.3% KOH as catalyst and molar ratio of methanol to oil 6:1 at 64 °C. Kumara et al. [105] revealed that purity and conversion of biodiesel was 99.04% using a continuous coil flow reactor at 70 °C with potassium hydroxide as a catalyst and oil to methanol molar ratio 1:5.

6.3. Calophyllum inophyllum biodiesel

The three stage production processes of a biodiesel from a non-edible oil Calophyllum inophyllum Linn via pre-treatment, alkali catalyzed transesterification and post treatment was carried out by Venkanna and Reddy [106]. The acid esterification with 0.5 ml anhydrous H_2SO_4 at 60 °C for 120 min at molar ratio methanol to oil 4:1 gave the maximum conversion efficiency of FFA to triglycerides. The acid value of Calophyllum inophyllum oil was reduced from 4.76 to 1.64 mg KOH/g during acid esterification reaction. The combination gave the optimum reaction conditions for alkali trans-

Table 9
Transesterification reaction using various types of catalyst for palm biodiesel.

No	Catalyst	Molar ratio of methanol	Biodiesel yield	Duration (h)	Temp (°C)	Ref.
1	H_2SO_4	8:1	99.5	1	70	[43]
2	KOH/Al_2O_3 and KOH/NaY	15:1	91.1	2–3	70	[81]
3	H_2SO_4	40:1	97.0	9	95	[82]
4	Montmorillonite KSF	8:1	79.6	3	190	[83]
5	KF/Ca–Al	12:1	99.7	3	65	[84]
6	Not applicable	30:1	72	0.33	360	[85]

esterification of Calophyllum inophyllum oil was found to be molar ratio of methanol to oil 8:1, 1.25% KOH, at 60 °C temperature and 120 min reaction time. After that, it followed by thrice gentle washing of the biodiesel with distilled water (30%, v/v) of 60 °C. The yield of biodiesel from the Calophyllum inophyllum oil under the optimized conditions is found to be 89%. The Calophyllum inophyllum biodiesel obtained by this process is suitable use in direct injection diesel engines [106].

On the other hand, Sahoo et al. [49,75] produced high viscous (72 mm^2/s at 40 °C) and high acid value (44 mg KOH/g) Calophyllum inophyllum oil based mono esters (biodiesel) by triple stage transesterification process and blended with diesel in a single cylinder diesel engine. A three step process is acid base process, acid-pretreatment and followed by main base transesterification reaction using methanol as reagent as well as H_2SO_4 and KOH as catalysts to produce biodiesel from Calophyllum inophyllum oil [49]. The viscosity of Calophyllum inophyllum oil reduces substantially after transesterification. The density and viscosity of the Calophyllum inophyllum oil methyl ester formed after triple stage transesterification ands it is close to diesel oil. All the characterization tests of Calophyllum inophyllum biodiesel demonstrated and found that most of the properties are in very close agreement with the diesel oil [75]. Therefore, Calophyllum inophyllum biodiesel is a potential fuel for the application in compression ignition engines for complete replacement of diesel fuel without any modification of engine.

Two step process biodiesel from Calophyllum inophyllum oil by using phosphoric acid modified β-zeolite in acid catalyzed esterification process and transesterification process using alkali catalyst potassium hydroxide (KOH) was conducted by Selvabala et al. [107]. The authors concluded that phosphoric acid modified β-zeolite would be the better replacement for the conventional liquid acid catalyst.

Table 10 shows the summary of fuel properties of Palm, Jatropha and Calophyllum inophyllum biodiesel.

7. Performance of biodiesel

The findings and outputs for performance of biodiesel fuel in diesel engine are reviewed. The performance parameter such as brake thermal efficiency, specific fuel consumption and power output for palm oil, Jatropha curcas and Calophyllum inophyllum are discussed below.

7.1. Palm biodiesel

A study of combustion performance and exhaust emissions from the non-pressurised combustion of palm oil biodiesel blends were performed by Ng and Gan [108]. The study explores the correlations between emission species and fuel pumping pressures over a range of equivalence ratios (ERs). This experimental study shows that optimum combustion in non-pressurised burner system occurs over a narrow band of ER values from 0.75 to 0.85. The combustion quality was offset by the accompanying increase in NO level when the POME content is raised [108]. de Almeida et al. [109] work proved that a diesel engine can be adapted to run will with palm oil and with increasing the palm oil temperature the performance and endurance of the diesel engine increases. The palm oil presented lower viscosity, better combustion and less deposit when heated at 100 °C. However, the specific fuel consumption of palm oil in diesel engine is slightly higher than diesel fuel [109]. The performance of palm diesel with 4-Nonyl phenoxy acetic acid (NPAA) as additive to control NO_x and CO in diesel engines was conducted by Kalam and Masjuki [110]. The findings found that palm diesel blend with 1% of NPAA produces higher brake power and lower specific fuel consumption compared to diesel fuel and palm diesel. Due to oxidative characteristics biodiesel causes more corrosion and wear to engine parts by using anti-wear additives, it is shows a significant reduction of wear properties [110]. Therefore, 1% NPAA additive in palm diesel is useful to produce better combustion in diesel engine compared to diesel fuel. Hence, the NPAA additive is effective in palm diesel fuel.

The results of performance and durability tests in a diesel engine with crude palm oil were analyzed by Bari et al. [111–112]. From the study, it is observed that preheating of CPO lowered viscosity and provided smooth fuel flow but did not affect the injection system, even heating up to 100 °C. However, combustion analyses comparisons show that CPO produced a higher peak pressure of 6%, shorter ignition delay of 2.6°, lower maximum heat release rate and a longer combustion period compared to diesel fuel [112]. Apart from that, it is shows that heavy carbon deposits in the combustion chamber, wear of piston rings, uneven spray formation and scuf-

Table 10
Summary of fuel properties of Palm, Jatropha and Calophyllum inophyllum biodiesel [24,43,49,101,107].

Properties	Unit	Palm biodiesel	Jatropha biodiesel	Calophyllum inophyllum biodiesel	ASTM D6751-06 standard
Density at 15 °C	kg/m^3	879.3	862	869	860–900
Cetane number	–	52	57	57	47 min
Viscosity at 40 °C	mm^2/s	4.9	4.8	4.0	1.9–6.0
Flash point	°C	181	135	140	130 min
Cloud point	°C	15	6	13.2	−3 to 12
Pour point	°C	14	2	4.3	−15 to 10
Calorific value	kJ/kg	–	39,230	41,397	–
Distillation 90%	°C	335	–	356	360 max
Water content	wt%	0.03	0.025	0.005	0.030 max
Ash content	wt%	0.0066	0.012	–	0.020 max
Carbon residue	wt%	0.07	0.2	–	–
Acid value	mg KOH/g	0.33	0.4	1.62	0.8 max

fling of the cylinder lining when using the crude palm oil in diesel engine [111]. Lin et al. [113] investigated the fuel consumption and energy efficiency from the diesel engine under steady state for different blends of palm oil biodiesel and diesel. The results showed that brake specific fuel consumption increased with rising palm biodiesel blends due to the low gross heat value of palm biodiesel. Sapuan et al. [114] concludes that power output was almost same for neat palm oil, blend of palm oil diesel fuel and pure diesel fuel. Short-term using of palm oil fuel showed no adverse effects.

7.2. *Jatropha biodiesel*

The effect of brake power on the brake thermal efficiency and ignition delay for Jatropha oil methyl esters (JOME) was presented by Banapurmath et al. [66]. There is a steady increase in efficiency as the load increases in the JOME operation. The brake thermal efficiency is 29% with JOME and its lower compared to diesel fuel. This is due to poor mixture formation as a result of the low volatility, higher viscosity and density of the Jatropha oil. The ignition delay for JOME is 11.5° CA operations at 80% load [66]. Pramanik [67] revealed the performance of using Jatropha oil and diesel fuel blends in compression ignition engine. There are significant improvements in engine performance when compared to neat Jatropha oil. The specific fuel consumption was reduced due to decrease in the viscosity of the Jatropha oil. Acceptable brake thermal efficiency (26.1%) of engine has achieved with the blends containing up to 50% Jatropha oil. Blends with a lower percentage of Jatropha oil showed slightly higher exhaust gas temperatures compared to diesel oil but still much lower than the Jatropha curcas oil. Chauhan et al. [115] investigated the evaluate suitability of Jatropha curcas oil (unheated and preheated) as an extended fuel for CI engine and to evaluate the performance and emission characteristics of the engine. Experimental results show that the engine performance with unheated Jatropha oil is slightly inferior to the performance with diesel fuel. As fuel inlet temperature of Jatropha oil increased, viscosity decreased, thus the engine performance improved. The results show that thermal efficiency of the engine was higher and brake specific energy consumption of the engine was lower when fuelled with preheated Jatropha oil compared to diesel fuel [115]. A 100 °C of fuel inlet temperature of Jatropha oil, performance and emissions were favourable but leakage of lube oil occurred. Therefore, 80 °C was evaluated as the optimal fuel inlet temperature, considering the BTE, BSEC, gaseous emissions and safe operation of the engine. Thus, by using heat exchanger preheated Jatropha oil can be a good substitute fuel for diesel engine.

Being a fuel of different origins, the standard design parameters of a diesel engine may not be suitable for Jatropha methyl ester. Therefore, Jindal et al. [116] demonstrated that increase in compression ratio associated with increase in injection pressure improves brake thermal efficiency and fuel consumption by Jatropha methyl ester fuelled diesel engine. The highest performance is delivered by the engine at 250 bar injection pressure and compression ratio 18 which BSFC improves by 10% and BTE improves by 8.9% [116]. Agarwal and Agarwal [117] evaluated the performance characteristics of Jatropha oil preheats and blends in a direct injection compression ignition engine. It was found that heating the Jatropha oil between 90 °C and 100 °C is adequate to reduce the viscosity and close range to diesel. Based on BSFC, thermal efficiency, and smoke opacity, 200 bar is the optimum fuel injection pressure for preheated Jatropha oil and diesel. Therefore, preheating the Jatropha oil does not lead to change the optimum fuel injection pressure. In the other hand, viscosity of Jatropha blends (up to 30%) was also close to diesel. BSFC was increase with higher proportion of Jatropha oil in the blend compared to diesel in the entire load range. However, thermal efficiency was found to be lower for higher blend concentrations compared to diesel oil. Kumar et al. [118] analyzed the use of methanol and Jatropha oil in a compression ignition engine. In the studies comparison of Jatropha oil, transesterification of Jatropha methyl ester and Jatropha oil methanol blend (30% methanol) were studied experimentally. The maximum brake thermal efficiencies are 27.4%, 29% and 28.1% with Jatropha oil, Jatropha methyl ester and Jatropha oil methanol blended. Ignition delay and combustion duration are increased with Jatropha oil, methyl ester of Jatropha oil and Jatropha oil methanol blend as compared to diesel. Besides, Reddy and Ramesh [119] performed the effect of injection timing, injector-opening pressure, injection rate and air swirl level on the performance of Jatropha oil fuelled diesel engine. The injection timing was varied by changing the position of the fuel injection pump with respect to the cam. A properly oriented masked inlet valve was employed to enhance the air swirl level. It is shows that with advancing the injection timing and increasing the injector opening pressure increase the BTE from 26.2% to 28.9% compared to neat Jatropha oil. On the other hand, the ignition delay with Jatropha oil is always higher than that of diesel under similar conditions.

The performance of diesel engine fuelled with Jatropha oil using hot exhaust gas recirculation (EGR) was carried out by Pradeep and Sharma [120]. The results indicated that with increasing the EGR level the BTE reduced significantly. Percentage reduction in BTE over an EGR range of 0–25% was 4.9% for Jatropha oil. The drop in efficiency at higher levels of EGR is possibly due to predominant dilution effect of EGR leaving more exhaust gases in combustion chamber. Haldar et al. [121] prepared blend Jatropha oil by degumming method and the performance characteristics of a diesel engine was studied. Degumming is an economical chemical process of acid treatment by which the gum of the vegetable oil is removed to improve the viscosity and cetane number of vegetable oil up to certain limit [121]. 20% blends of degummed Jatropha oil give a better performance of brake specific fuel consumption and brake thermal efficiency than diesel oil in compression ignition engine. It is showed that the Jatropha oil gives the best performance and emissions at high loads and 45° bTDC injection timing. Sahoo et al. [20] evaluated the performance and emission characteristics of Jatropha and Calophyllum inophyllum based biodiesel as fuel in a compression ignition engine. The study findings show that maximum increase in power is 50% Jatropha biodiesel (JB50) at 2000 and 2100 rpm. Brake specific fuel consumptions for all the biodiesel blends with diesel increases with blends ratio and decreases with speed. The best brake specific fuel consumption improvement is observed with JB20 [20]. The ignition delays were consistently shorter for neat Jatropha biodiesel varying between 5.9° and 4.2° crank angles lower than diesel with the difference increasing with the load [122].

An experimental study of the performances and emissions in a diesel engine using Jatropha oil was prepared by Huang et al. [123]. The engine performance and thermal efficiency run Jatropha biodiesel are comparable to pure diesel fuel. However, the fuel consumptions of engine are slightly higher when fuelled Jatropha biodiesels [123]. Forson et al. [124] conducted the performance of Jatropha oil blends in a diesel engine. The 97.4%/2.6% fuel blend yield the highest cetane number and even better engine performance than the diesel fuel [124]. Chauhan et al. [125] also tested the performance and emission studies on an agriculture engine fuelled with neat Jatropha oil.

7.3. *Calophyllum inophyllum biodiesel*

Sahoo et al. [20,122] evaluated the combustion analysis, performance and emission characteristics of Calophyllum inophyllum based biodiesel as fuel in a diesel engine. The results show that neat Calophyllum inophyllum biodiesel (CB100) which results in maxi-

Table 11
Research findings of brake thermal efficiency (BTE) from biodiesel combustion.

BTE	Palm oil	Jatropha curcas	Calophyllum inophyllum
BTE increase	de Almeida et al. [109], NPAA additive: Kalam and Masjuki [110]	Diesel blend: Pramanik [67], preheated: Chauhan et al. [115], Jatropha methanol blend: Kumar et al. [118], Retard the injection timing: Reddy and Ramesh [119], Degummed Jatropha blend: Haldar et al. [121], Huang et al. [123]	
BTE decrease		Blend J20: Agarwal and Agarwal [117], JOME: Banapurmath et al. [66], Hot EGR: Pradeep and Sharma [120]	Blend: Sahoo et al. [20,122]

mum peak cylinder pressure (6.61 bars higher than that of diesel) is the optimum fuel blend as far as the peak cylinder pressure is concerned [122]. There are no significant change in power for diesel engine at lower speeds 1200 and 1400 rpm for Calophyllum inophyllum biodiesel. However, slight reduction in power is observed at all the speeds with biodiesel blends of 20% and 50% Calophyllum inophyllum biodiesel (CB20 and CB50). Besides, it is observed that there is an improvement in fuel economy with CB20 compare with diesel fuel [20]. The ignition delays are shorter PB100 which is varying between 5.7° and 4.2° CA lower than diesel fuel. On the other hand, the peak pressure for CB100, CB50 and CB20 is 85.31 bar occurring at 5° CA after TDC, 84.1 bar occurring at 5.1° CA after TDC and 80.9 bar occurring at 5.2° CA after TDC respectively which is 6.61 bar, 5.4 bar and 2.2 bar higher than diesel respectively [122]. The optimum engine operating condition based on lower brake specific fuel consumption and higher brake thermal efficiency was observed at 100% load for neat Calophyllum inophyllum biodiesel [75].

Table 11 shows the research findings of brake thermal efficiency from palm oil, Jatropha curcas and Calophyllum inophyllum biodiesel in diesel engine.

8. Emissions of biodiesel

Biodiesel mainly emits carbon monoxide, carbon dioxide, nitrogen oxides, sulphur oxides and smoke. The ignition timing, fuel contents and fuel viscosity will affect emission exhaust from engine. Apart from using additives fuel properties by preheating or oxidizing, many aftertreatment devices such as particulate matter filter, exhaust gas recirculation (EGR) are used. A brief review of the most prominent engine emissions from biodiesel is discussed in this section.

8.1. Palm biodiesel

Many researchers have claimed reduction of CO_2 emission whereas some studies reported that South East Asia emit excessive emissions from palm oil biodiesel. Kalam and Masjuki [126] conducted the study for emissions characteristics of a small diesel engine operated on preheated crude palm oil (CPO). It was observed that preheated CPO reduced CO, HC and PM compared to diesel and CPO emulsified fuel. Preheating of CPO reduces its viscosity to the level of diesel fuel that improves the fuel spray and atomization characteristics and produces complete combustion. However, preheated CPO increased NO_x emission compared to diesel and CPO emulsified fuel [112,126]. This is mainly attributed from the deposit characteristic result and shows that preheated CPO increased the highest fraction of ash deposit, which is the cost of increasing NO_x emissions [126]. Besides, Kalam and Masjuki [110] tested palm diesel and 4-Nonyl phenoxy acetic acid (NPAA) as additive to control NO_x and CO in diesel engines. The result shown that NO_x, CO and HC concentration decrease by using palm diesel with additive compared to diesel fuel and Palm biodiesel. Hence, the NPAA additive is effective in palm diesel fuel. Besides, Kalam and Masjuki [127] also shown that anticorrosion additive was effective with palm diesel blends to reduce NO_x emissions.

The effects of antioxidant additives on pollutant formation from the combustion of palm oil methyl ester blends with diesel in a non-pressurised burner were carried out by Gan and Ng [128]. The study shows that with proper selection of additives type and quantity for application to biodiesel blends, it is to be an effective pollutants control strategy which is more economical than other existing technologies. Reijnders and Huijbregts [129] concluded that the total emissions in CO_2 equivalent associated with met losses due to plantation practices, the use of fossil fuel in the palm oil life cycle and anaerobic conversion of palm oil mill effluent is about 2.8–19.7 kg CO_2 equivalent per kg of palm oil. Carbon monoxide (CO) level was found to be minimal when ER is within the 0.75–0.85 range and the exhaust CO improved across the tested ER range with increasing POME proportion in the fuel blends [108]. Lin et al. [113] investigated the polycyclic aromatic hydrocarbons (PAHs) emission and particulate matter of palm biodiesel blend fuel. Kousoulidou et al. [130] studied the palm biodiesel blend effects on common-rail diesel emissions and compared against a Euro 3 common-rail light duty vehicle. The results show that palm biodiesel blends reduced PM emissions and only marginal effects on NO_x over the certification test.

8.2. Jatropha biodiesel

The study of effects of fuel inlet temperature (FIT) on engine emissions using a dual fuel engine test rig with tube heat exchanger was investigated by Chauhan et al. [115]. Results show that the NO_x emissions from Jatropha oil were increases with increase in FIT. However, with preheated Jatropha oil, the value of CO, HC and smoke opacity was decreased and CO_2 emissions were slightly increased [115]. Banapurmath et al. [66] study the emission characteristics of a DI compression ignition engine operated on Jatropha oil methyl esters (JOME). The effects of brake power on smoke opacity, HC and CO for JOME were higher compared to the standard diesel oil. However, NO_x emissions were lower for JOME compare to diesel oil due to low cylinder peak pressure and lower heat release rate [66]. On the other hand, Agarwal and Agarwal [117] evaluated the emissions characteristics of Jatropha oil blends in a direct injection compression ignition engine. The results show that the emission parameters such as smoke opacity, CO_2, CO, and HC were increased with increasing proportion of Jatropha oil in the blends compared to diesel.

Kumar et al. [118] study shown that the maximum smoke level for Jatropha oil is 4.4 BSU, Jatropha methyl ester is 4 BSU and Jatropha methanol blend is 4.1 BSU which is higher compared with diesel (3.8 BSU). Besides, HC and CO emissions also slightly increase with Jatropha methyl ester and Jatropha methanol blend compared to diesel oil. However, NO emissions level was lower with Jatropha oil compared to diesel and it is further reduced in Jatropha methanol blend. Reddy and Ramesh [119] evaluated that advancing the injection timing and increasing injection pressure reduce HC, CO and smoke emissions significantly using Jatropha oil as fuel in diesel engine. Besides, NO emissions reduction is achieved by increasing injection pressure as well as advancing injection timing with Jatropha oil fuelled compression ignition engine [119]. Pradeep and Sharma [120] suggested that use of hot exhaust gas

Table 12
Summary of research findings related to emission from biodiesel.

Emissions	Palm oil	Jatropha curcas	Calophyllum inophyllum
CO_2 increase		Blended: Agarwal and Agarwal [117]	
CO_2 decrease		Preheated: Chauhan et al. [115], Degummed Jatropha blend: Haldar et al. [121]	
NO_x increase	Preheated: Kalam and Masjuki [126], Preheated: Bari et al. [112], Kousoulidou et al. [130]	Preheated: Chauhan et al. [115]	Blend: Sahoo et al. [20]
NO_x decrease	NPAA additive: Kalam and Masjuki [110], Corrosion inhibitor additive: Kalam and Masjuki [127]	JOME: Banapurmath et al. [66], Jatropha methanol blend: Kumar et al. [118], Retard the injection timing: Reddy and Ramesh [119], Hot EGR: Pradeep and Sharma [120], Degummed Jatropha blend: Haldar et al. [121], Huang et al. [123]	
HC/CO increase		JOME: Banapurmath et al. [66], Blended: Agarwal and Agarwal [117], Jatropha methanol blend: Kumar et al. [118]	CO increase; HC decrease Blend: Sahoo et al. [20]
HC/CO decrease	NPAA additive: Kalam and Masjuki [110], Preheated: Kalam and Masjuki [126]	Preheated: Chauhan et al. [115], Retard the injection timing: Reddy and Ramesh [119], Degummed Jatropha blend: Haldar et al. [121], Huang et al. [123]	
Smoke opacity increase		JOME: Banapurmath et al. [66], Blended: Agarwal and Agarwal [117], Jatropha methanol blend: Kumar et al. [118]	
Smoke opacity decrease		Preheated: Chauhan et al. [115], Retard the injection timing: Reddy and Ramesh [119]	Blend: Sahoo et al. [20]

recirculation (EGR) for oxides of nitrogen control in diesel engine fuelled with Jatropha oil can effectively reduced NO_x emission. However, 15% of EGR was optimized level to reduce NO_X emission without much adverse effects on the performance, smoke and other emissions.

The CO, CO_2, NO_x and HC emissions for degummed Jatropha blend are lower in comparison to diesel at high loads [121,123]. However, at low loads the emissions for Jatropha are almost parallel to diesel. It is due to higher ignition temperature and better combustion of Jatropha oil gives less exhaust emissions than diesel [121,123]. Jindal et al. [116] analyzed that with increasing the compression ratio and injection pressure, the emissions of HC, NO_x, smoke opacity and exhaust temperature are lower with pure Jatropha oil compare with diesel fuel. Raw Jatropha oil and Jatropha methyl ester both emit more smoke and PM. However, Jatropha biodiesel methyl ester emits more HC and CO compared to diesel fuel. Preheating Jatropha oil and using in lower proportion blends with diesel have reduced emissions.

8.3. *Calophyllum inophyllum biodiesel*

The study of emissions for Calophyllum inophyllum biodiesel use as substitute fuel in a diesel engine was tested by Sahoo et al. [20]. Test data were generated during part throttle test mode show that blend with higher percentage of Calophyllum inophyllum biodiesel in diesel tends to decrease the exhaust smoke substantially. Besides, it is noticeable reduction in HC and PM is seen with Calophyllum inophyllum biodiesel. However, there is a slight increase in CO and NO_x. The neat Calophyllum inophyllum biodiesel was shown reduced in exhaust emission as compared to diesel evaluated by Sahoo et al. [75].

The summary of research findings related to emissions from palm, Jatropha and Calophyllum inophyllum biodiesel as shown in Table 12

9. Conclusions

Biodiesel fuel is gaining more interest as an attractive alternative fuel due to the environmental pollution and diminishing supply of fossil fuel. Biodiesel has similar combustion characteristics as diesel and biodiesel blend can reduce hydrocarbons, smoke opacity, particulate matters, carbon dioxide and carbon monoxide emissions but NO_x emissions have slightly increased. However, exhaust emissions of NO_x can be controlled by adopting certain strategies such as changing the composition of feedstock, improve the cetane number, retardation of injection timing and exhaust gas recirculation. On the other hand, the main drawbacks of vegetable oil have to overcome due to the high viscosity and low volatility which will cause a poor combustion in diesel engines. Several ways to reduce the problem of high viscosity are preheating the oil, microemulsion with solvents, dilution with diesel fuel, thermal cracking or pyrolysis and transesterification.

In Malaysia, it is economically viable to use palm oil as a feedstock for producing biodiesel as Malaysia is one of the world's leading producers and exporters of palm oil. Palm oil is one of the most efficient oil bearing crops in terms of land utilization, efficiency and productivity. However, competition of edible oil sources as food with fuel makes edible oil not an ideal feedstock for biodiesel production. This shifts the attention to non-edible oil like Jatropha curcas and Calophyllum inophyllum oil which are grown in tropical and subtropical climates country. Jatropha has an extra advantage over other non-edible oil sources as it is a drought-resistant plant capable of surviving in abandoned and fallowed agricultural land. Besides, Calophyllum inophyllum oil can be considered as a potential biodiesel fuel and could be transesterified. However, compared to Palm oil and Jatropha biodiesel industry, biodiesel from Calophyllum inophyllum is still in its nascent state in Malaysia. Therefore, further study and research on biodiesel fuel property characteristic, long-term wear and tribological analysis along with injection timing and duration for better combustion in diesel engines need to be carried out.

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